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Solar-powered smart window design with aerosol trap and greenhouse gardening

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ABSTRACT

The work is devoted to the development and testing of a solar-powered device with the functions of dust and other aerosol particles capturing both inside and outside the room, with the ability to regulate the light and heat fluxes into the room and with the greening function. The purpose of the device development is the use of solar energy in window household systems for: 1) night and adjustable daytime lighting of rooms; 2) cleaning the city's air basin from dust and burning, 3) additional heat and sound insulation. A working model scaled down to 1:5 was created, where consumer functions were tested and finalized after modeling in AutoCAD. The device based on solar panels provides a combination of the mentioned consumer functions having three autonomous modules. They are placed on a united metal structure that is fixed in the opening and on the window frame. The model provides five static and three dynamic modes of device operation. The developed device can be used to improve the ecology of the urban environment.

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1. Introduction

The use of photovoltaic panels in urban conditions, only for energy generation, unfortunately, is unprofitable despite significant progress in increasing the efficiency of solar panels based on crystalline silicon [1–3], and the intensive development of organic [4], perovskite [5,6] and photoelectrochemical cells [7]. However, since energy from traditional energy sources is much cheaper and the infrastructure for transporting energy to end users in cities has already been formed, even using efficient solar panels will not make their operation for intended use cost-effective. However, if the end user is offered not only electricity, but a household device with a combination of LED illuminator and external blinds from panels regulating sunlight, then the commercial attractiveness of the device will significantly increase [8,9].

In cities where a high concentration of aerosol particles strongly affects the health of residents and the comfort of their stay, systems are being developed that can capture particles from the ambient air [10,11] and reduce heat loss in premises [12,13]. Thus, preventing fatal climate change requires more than just limiting aerosols and greenhouse gas emissions, as well as turning territories into absorbers of emissions and dust, as well as dispersing the population across steppe and desert regions and landscaping, as planned in the Sahara [14] or the Middle East [15].

The proposed device, located close to people's homes, will allow the use of the surrounding alternative energy to improve the climate and is one of the few ways to prevent an environmental disaster. The relevance of the study is also associated with measures to reduce greenhouse gas emissions not only by saving energy from carbon sources replaced by alternative ones, but also by absorbing them by illuminated and insulated "green" facades. It also helps to solve the problem of the cost-effective use of alternative energy sources.

2. Design of the device

2.1. Description of the functional diagram of the mechatronic system of smart windows

Fig. 1 shows the functional diagram and provides a combination of several consumer properties of the device and a combination of

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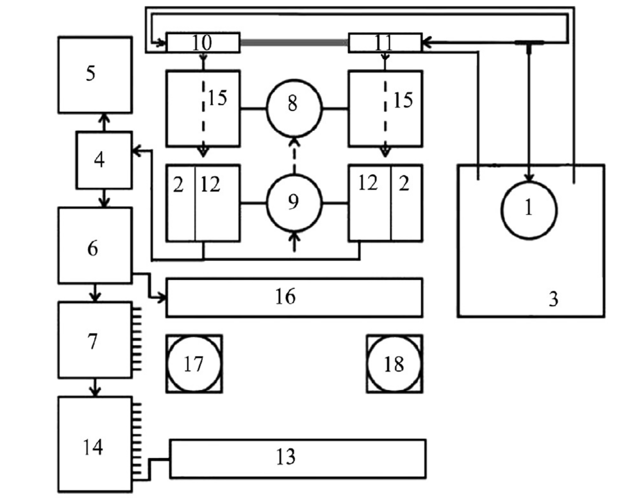


1 - submersible pump; 2 - Green panel; 3 - bath; 4 - Battery charge controller; 5 - Battery; 6 - Power supply unit; 7 - Automation unit; 8 - Motor plate reducer; 9 - Motor reducer of panels; 10.11 - Wipers with spray panels and plates; 12 - Solar panel; 13 - LED Illuminator; 14 - Switchgear; 15 - Acrylic plates; 16 - High voltage electrode; 17.18 - Fan;

Fig. 1. Functional diagram of a household window system for regulating light and heat fluxes, self-cleaning and dust collection.

three autonomous modules located on a single metal structure fixed in the opening and on the window frame. The motor reducer 9 moves up and down along the guides solar panels 12 and plant panels 2 at the same time. The submersible pump 1 supplies water for washing the platinum 15 or for watering plants and washing solar panels, at the time of changing the position of the plates or panels. The motor reducer 8 moves the acrylic plates 3 along with the structure to one of three static positions, depending on the control program set in the automation unit 7. In the process of moving the plates 15 and panels 12 and 2, the plates can be cleaned with wipers 10,11, into which washing liquid or water from the bath 3 can be sprayed.

Photovoltaic energy from the solar panel 1, through the controller 4 enters the battery 5, from which through the same controller 4 power is supplied to all electronic and electromechanical components of the device, including the automation unit 7, which controls the logic of the entire device and the executive control panel 14. In the mode collecting dust, the fans 17, 18 are turned on and a high voltage is applied to electrode 16. Washing and collection of the dust deposited on the front dielectric surface of the plates is carried out by humidified wipers 10, 11 with watering them with water from the bath 3 with a submersible pump 12 during the lifting of the plates no more than daily. Acrylic plates 15 and panels 12.2 can carry out room dimming, sound insulation and room thermal insulation. The devices of the fire and security alarm modules, as well as the "parental window lock" module are not listed and are included in additional consumer modules.

The original functions are performed by acrylic plates: they protect the front panels from dust and dirt and at the same time extract fine dust from the air ascending along the facade of the building, they are a heat shield for an impromptu outdoor greenhouse, they are an element scattering direct sunlight, they act as an additional sound screen. The dust is washed off by stationary wipers with humidification, and the stream of water carries the dust into the bath with water, where it settles.

2.2. Layout sample

A full-size model of the device was made at the window of the Physics and Technology Faculty of al-Farabi KazNU. Note that the force calculations were carried out for the version of a full-scale prototype.

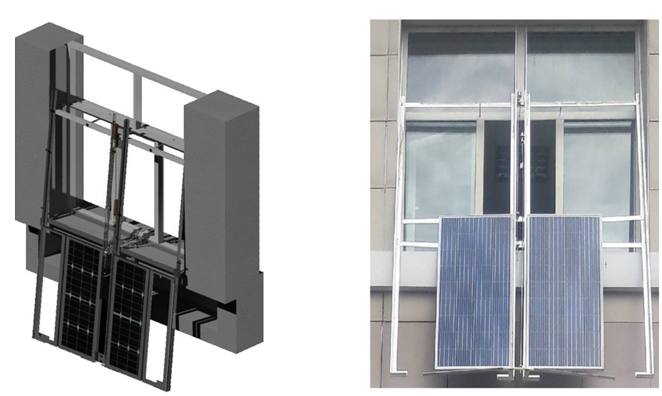
In a life-size model, mounted on a real window opening, it is also necessary to consider the design of the window opening in the building to distribute a large static load, which can reach 70 kg, and an additional dynamic load, which reaches 400 N/m^2 with a wind of 20 m/s protruding from the opening of the flat plate. The plastic window frame and sill will not withstand a dynamic load of 150 kg, so the frame had to be reinforced with two frames made of 50x50x4 duralumin corners. This design acts as a powerful crossbar that can carry a load of more than 200 kg.

Fig. 2a shows a drawing with a slide for solar panels (with corresponding materials) [3]. The latter are attached to the slider of a helical gear made on a stud with a metric thread. The presence of such a thread makes it possible to use self-locking of the thread to save energy, since in static mode this circumstance makes it possible to disconnect the motor-reducer from the battery, and not brake it with a reverse current.

Fig. 2b shows a photo of the layout, with two solar panels, hung out. The panels are attached to the slider and are themselves guides that fix the direction of movement. However, distortions and deformations of the long pin are possible due to the curvature of the corners and errors in their installation. This circumstance requires the use of a thick elastic cushion between the slider and screw-type gear's nut as well as increase the rotational moment of the shaft of the gear motor, reducing the frequency of shaft rotation.

Each of the two panels, with an area of 0.85 m^2, can be located on the eastern and southern facades and, in clear weather, per day can accumulate from 0.1 to 1 kW*h of electricity in the battery, depending on the location and season. All electricity is used only for the operation of window construction devices and a greenhouse illuminator. In cloudy weather and at night, even from the general network, additional energy must be taken, since the dust collection system can work as a system for capturing aerosol particles and must work continuously. When the dynamic modes and greenhouse lighting are turned off, 2 pcs of 1 kW*h batteries can be used as a backup source of electricity, especially in case of power outages.

Acrylic plates and a charging electrode are used to collect particles and aerosols from the atmosphere. For the panels not to be idle at night and not be contaminated, it is advisable to cover them with acrylic plates, which, in turn, with this area can remove particles charged by the electrode from the atmosphere. In the atmosphere, upward currents with turbulent jets are formed along the facades, which ensure that atmospheric particles touch the electrode and plates, ensuring their charge and adhesion to the plates. The estimated number of particles caught in grams per day can



a) 3D layout [8] b) Picture of the layout

Fig. 2. Frame with sleds for solar panels.

range from 0.1 to 100 g per window, depending on many factors [16].

The radiation heat flux from the sun into the room, as well as the luminous flux, has 5 gradations, according to the number of static modes, however, these gradations are not uniform and depend on the season and the location of the window on the facade. The same is the case with the flow of heat from the room into the atmosphere. Convective heat fluxes are also superimposed on the radiation fluxes, the gradation of which is determined by the number of static modes.

3. Results and discussion

Before the manufacture of the prototype [3], a working model was made on a scale of 1:5. The model provides five static and three dynamic modes of device operation.

3.1. Dynamic modes of operation

In the *first dynamic mode*, the electric motor of two screw drives of the translational motion of solar panels and protective acrylic panels operates. Thus, we can move the panels and plates upwards either alternately or simultaneously with the electrode turned on.

In the *second dynamic mode* and protective acrylic panels, the panels and plates move downward by an electric motor. If snow has adhered to the solar panels - the lower edge of the plates throws snow from the solar panel when going down.

In the *third dynamic mode*, the electric motors are turned on, the voltage is removed from the charging electrode, and the submersible pump is turned on, supplying a washing or disinfecting solution to acrylic plates or a nutrient solution to a plant panel. Thus, in dynamic modes, acrylic panels can be washed by moving them upwards from the position indicated in Fig. 3a to the position indicated in Fig. 3b. If the solar panel and the plant panel are moved upwards from the position in Fig. 3a, the plant panel is watered.

3.2. Static operating modes

In *static mode 1*, solar and plant panels, together with acrylic plates, are lowered down, namely, they are in the lowest position (Fig. 3a). This position is optimal in the absence of sunlight. The photoreceiving surface of solar panels is protected from dirt and debris by an acrylic plate, and the process of collecting electrified aerosol particles takes place. At this time, a high voltage is applied to the dust-charging electrode and the outer surface of the acrylic plates collects electrified aerosol particles, which can be washed off and decontaminated in a dynamic mode 3.

In *static mode 2* (photovoltaic power generation mode) in Fig. 3b, the system assumes a static position of maximum photovoltaic efficiency, in which the acrylic panel completely opens the solar panel. In this case, the solar panels and/or the plant panel are illuminated by the direct rays of the sun. Note that if the window is located on the western or eastern façade, the daily exposure will reach its maximum in the summer season. In the winter season, the maximum daily exposure is achieved for the device on the southern facade of the building. Acrylic plates with a diffuser glued on the backside (thin polyethylene foam or foam film on the inner surface of the plates) partially attenuate direct sunlight and absorb sound waves. Lateral and frontal technical slots are closed with decorative heat-insulating material such as polyurethane and penoplex.

In *static mode 3* (heat and sound shielding mode, Fig. 3c), acrylic plates with glued polyethylene foam are lifted up to the maximum and pressed tightly against the seals of the upper border of the window opening. Direct sunlight scatters and does not penetrate into the room, and an additional barrier with sound-absorbing material appears in the path of sound waves from the street. An additional obstacle also appears in the path of the heat flow from the room, and the external window sill and the system of plates and panels form an impromptu greenhouse, which is heated by the heat flow of the room at night.

In *static mode 4*, reinforced greenhouse thermal shielding (Fig. 3d) solar panels, vegetable panels and acrylic plates are positioned at the window level. Thus, the heating of the vertical plant plate, especially at night, comes from the room by supplying warm air into the space between the panels and the window. In the same space, you can place a horizontal panel of vegetation and illuminate it with artificial lighting from LEDs located above it and through the glass to illuminate the room. This is how an impromptu greenhouse will be organized. LED lighting will additionally warm up this space and warm up vertically located vegetation, although it is better to replace the vertically located plant panel with a solar panel, and the horizontal greenhouse will be more intensely illuminated and used in winter for growing green spices, strawberries, flowers and other food products. In this mode, you can turn on a high voltage to the dust-charging electrode and collect dust on the outer surface of the plates, and during a thaw, wash this dust into the dust collector.

In *static mode 5*, with a strong outside wind, to reduce the wind effect, it is necessary to hide the acrylic plates in the window opening as deeply as possible, so they rise as high as possible and press against the ceiling, Fig. 3e. The lower edge of the solar panels rises to the level of the outer window sill to exclude the impact on the panel of wind jets tearing it away from the panel wall. The transition from one static mode to another is carried out rather slowly, within 10–20 min, which is associated with the limitation of the power of the geared motors that move. The slowest will be the transition associated with the movement of solar panels up.

3.3. Dust washing system in dynamic mode

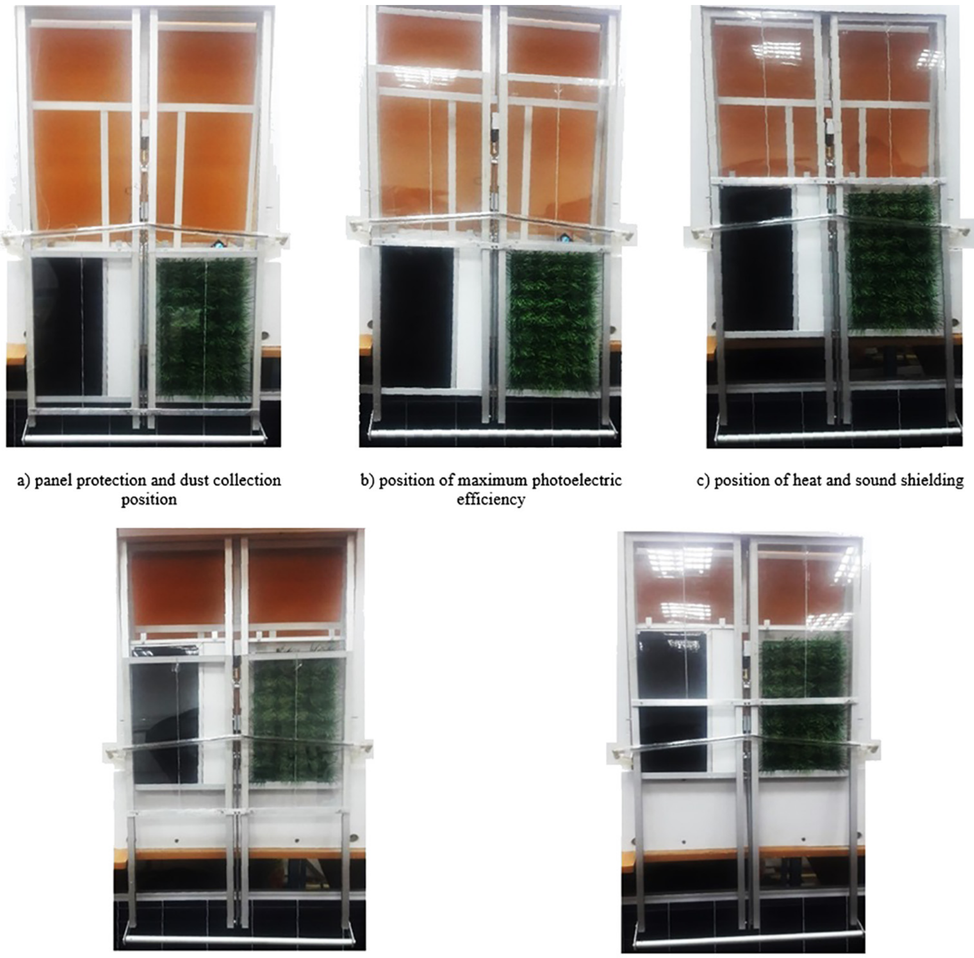
To test the system for washing acrylic plates and washing away dust, the option shown in Fig. 4 was chosen from several options.

The mechanism for washing the plates is as follows: A *submersible pump 1* through plastic hoses through a *tee 2* supplies water to an *acrylic tube 5* with holes that form 4–5 streams in each wiper. A stream with water and collected dust through the *collection system 6* and *pipes 4* returns water to the *bath 3*. On the operating model, the elements shown in the diagram are shown in Fig. 5a and b.

3.4. Scheme of air purification and disinfection

The accumulated energy from solar panels will also be directed to supply the electromechanical and disinfecting mechanisms of the window. To use simple mechanisms for air disinfection both outside and inside the rooms by removing suspended dust particles and ambient air is proposed in the system. Fig. 6 schematically shows the design of such a device.

Fan *1* directs air flow into *slotted tube 2* that charges aerosol particles. Then the air flow with particles is directed to the charged surfaces of the cavity made of film or *glass 3*, on which dust and aerosol from the air flow sits. Subsequently, the surface of the cavity is washed with a disinfectant solution. Part of the film and glass can serve as a sensor for analyzing the pollution of a public place or dustiness in the air. The device can be glued or hung on the *wall 4* in the room. Window glass can be used instead of film as well. During the work, it was found that dust particles contain water-soluble ionic particles, organic and elemental carbon, metals and have a fairly high electrical conductivity.



a) panel protection and dust collection position

b) position of maximum photoelectric efficiency

c) position of heat and sound shielding

d) position of the possible greenhouse heat shielding

e) position of maximum wind resistance

Fig. 3. Static operating modes test on the model of the developed device.

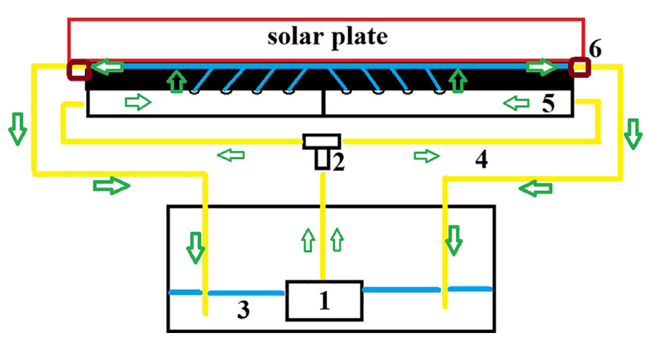


Fig. 4. Schematic view of washing away dust and dirt from acrylic plates.

Thus, when a dust particle touches the metal high-voltage electrode, the particle is fully charged and does not stick to it. In this case, the particle experiences the first disinfecting electric shock. Then the particle enters the space between the acrylic plates is reliably glued by touching them. So, the particle will not be carried away by air currents. The second and third disinfecting stages: irradiation with UV radiation of a movable lamp moving inside the cavity (without blowing) and washing off the dust with a liquid.

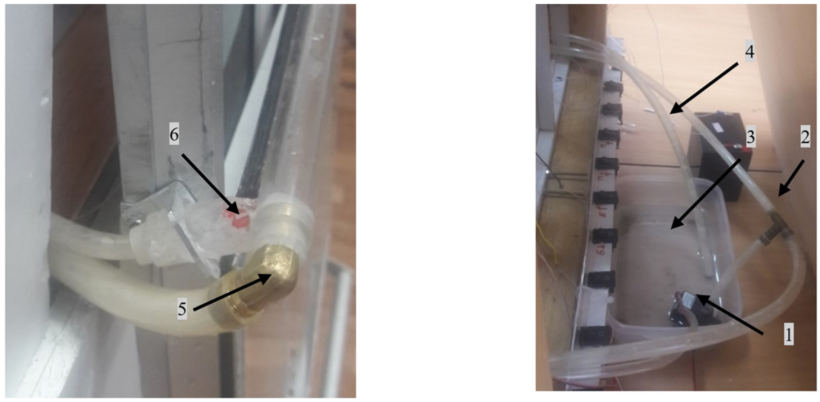
The developed device can be used in urban environments with a temperate climate, such as Almaty, Ust-Kamenogorsk, Beijing, etc., where there are environmental problems associated with dustiness.

4. Conclusion

The work substantiated the possibility of regulating light, sound and heat fluxes into and out of the room, the possibility of capturing aerosol particles, including infected ones, outside and inside the room by a household window system using solar energy. In the work, technical solutions for device installation, block mobility were selected, and a variant of using an additional green block was developed. Modeling of the technical part of the device was carried out in AutoCAD Mechanical. Also, a mock-up of the device was designed, made on a scale of 1:5 to test the implementation of the consumer functions of the device. This device can be used to improve the ecology of cities in temperate latitudes.

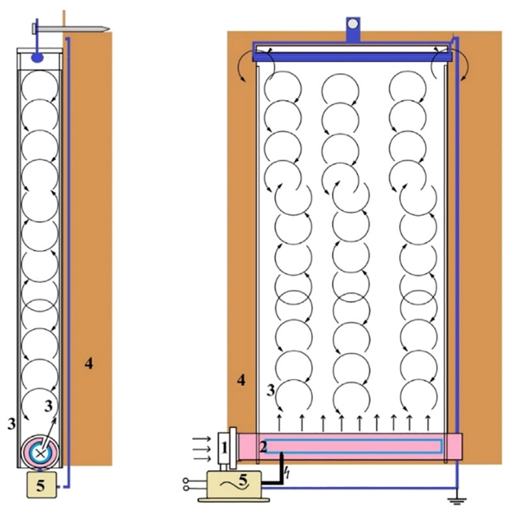
CRediT authorship contribution statement

Svetlana Mikhailova: Writing - original draft, Visualization. **Leonid Mikhailov:** Supervision, Funding acquisition, Writing - review & editing. **Guzal Ismailova:** Conceptualization, Project administration. **Nursultan Kenes:** Resources, Methodology. **Raiymbek Yersaiyn:** Investigation, Resources. **Ruslan Mahmutov:** Formal analysis, Software.



1 - submersible pump; 2 - tee; 3 - bath; 4 - pipe to return water; 5 - enter of water to an acrylic tube; 6 - return water collection funnel

Fig. 5. Washing dust and dirt from acrylic plates system.



1 - fan; 2 - charging tube; 3 - film or glass; 4 - wall or frame; 5 - electronic unit

Fig. 6. Device for capturing aerosol and dust particles indoors diagram.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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